Reacting Flows in Industrial Duct-burners of a Heat Recovery Steam Generator

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Motivation

Technological inconveniences concerning maintenance of the post-firing section of a Heat Recovery Steam Generator (HRSG) of an Integrated Gasification Combined Cycle (IGCC) power plant.
Layout of an IGCC power plant

A synthesis gas is produced by oxidising coal or waste products coming from petroleum distillation processes.
Syngas powers gas turbines that provide hot exhaust gases (Turbine Exhaust Gas, TEG) to a Heat Recovery Steam Generator (HRSG), producing working fluid for steam turbines.
The Heat Recovery Steam Generator

Very often the HRSG is equipped by a post-firing section, in order to balance losses in efficiency of the gas turbines (hotter season)
After-burners

The post-firing section consists in arrays of duct-burners, mounted on horizontally arranged pipes providing fuel by transversal nozzles.
What is the problem?

Duct-burners operative conditions are affected by fuel composition: gas impurities (Ni-carbonyl) becomes unstable at temperature above about 700 K, depositing metallic Ni on the burner contour.

It has been observed as high deposit thickness enables overheating, unusual thermo-mechanical stress and then cracking of the components.

The burners must be periodically cleaned to restore safe operating condition, imposing expensive plant stops.
This is a problem!
A multi-physical problem ...

Fluid-dynamics

Diffusion and transport of chemical species

Properties of fluids

Reaction enthalpy

Velocity field

Thermal analysis
Duct-burner array characterization

12 meters, 69 modules, 3 holes per module

89 MW_{th} - 133 MW_{th}

0.8 – 1.2 MW_{th}/m

“On design”
(100% thermal power)

“Turn down”
(150% thermal power)
Numerical model

One half section of the burner is considered both in 2D and 3D simulations.
Numerical model

Computational domain
Numerical model
Numerical model

Modelling and computations carried-out by COMSOL Multiphysics
Governing equations

Fluid dynamics: Newtonian fluid - Incompressible, turbulent and steady flow

\[(U \cdot \nabla)U = \frac{-\nabla p}{\rho} + \nabla \cdot [(\nu + \nu_T) \nabla U] + \frac{F}{\rho}\]

\[\nabla \cdot U = 0\]

\[(U \cdot \nabla)k = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \epsilon + \nabla \cdot \left[ \left( \nu + \frac{\nu_T}{\sigma_k} \right) \nabla k \right]\]

\[(U \cdot \nabla)\varepsilon = c_{\varepsilon 1} \frac{\varepsilon}{k} \cdot \tau_{ij} \frac{\partial u_i}{\partial x_j} - c_{\varepsilon 2} \frac{\varepsilon^2}{k} + \nabla \cdot \left( \nu + \frac{\nu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon\]

Momentum conservation
Continuity
Turbulent kinetic energy
Dissipated turbulent energy
Governing equations

Reacting flows and energy conservation

\[ CO + H_2 + O_2 \rightarrow H_2O + CO_2 \]
\[ \nabla \cdot (-D_{H_2} \nabla H_2) = R - U \cdot \nabla H_2 \]
\[ \nabla \cdot (-D_{CO} \nabla CO) = R - U \cdot \nabla CO \]
\[ \nabla \cdot (-D_{O_2} \nabla O_2) = R - U \cdot \nabla O_2 \]
\[ \nabla \cdot (-D_{H_2O} \nabla H_2O) = R - U \cdot \nabla H_2O \]
\[ \nabla \cdot (-D_{CO_2} \nabla CO_2) = R - U \cdot \nabla CO_2 \]

\[ R = \pm k_1 \times O_2 \times H_2 \times CO \mp k_2 \times CO_2 \times H_2O \]

Chemical reaction for syngas oxidation
(simplified)

Transport and diffusion of chemical species
\( (H_2, CO, O_2, CO_2, H_2O) \)

Reaction rate

Energy conservation

Net Enthalpy of reaction

\[ H = H_{CO_2} + H_{H_2O} -(H_{O_2} + H_{H_2} + H_{CO}) \]
Boundary Conditions

Fluid dynamics

**Incoming flow (TEG):**
- $u = u_{\text{teg}}$
- $k_0 = 0.018/4 \times (u_0_{\text{chke}}^2 + v_0_{\text{chke}}^2)$
- $\varepsilon_0 = 0.1643/0.09 \times (0.018/4)^{3/2} \times \sqrt{u_0_{\text{chke}}^2 + v_0_{\text{chke}}^2}^3$

**Outflow condition**

**Incoming flow (fuel):**
- $u = u_{\text{syn}}$
- $k_0 = 0.018/4 \times (u_0_{\text{chke}}^2 + v_0_{\text{chke}}^2)$
- $\varepsilon_0 = 0.1643/0.09 \times (0.018/4)^{3/2} \times \sqrt{u_0_{\text{chke}}^2 + v_0_{\text{chke}}^2}^3$

**Slip condition**

**Wall function**

**Products**
Boundary Conditions
Mass balance of chemical species

Incoming flux:
- $O_2 = \text{com}_v\cdot O_2 \cdot \rho_{\text{teg}} \cdot u_{\text{teg}} / \text{mm}_{\text{teg}}$

Fixed concentration:
- $H_2 = 0$
- $H_2O = 0$
- $CO = 0$
- $CO_2 = 0$

Incoming flux:
- $H_2 = \text{com}_v\cdot H_2 \cdot \rho_{\text{teg}} \cdot u_{\text{teg}} / \text{mm}_{\text{teg}}$
- $CO = \text{com}_v\cdot CO \cdot \rho_{\text{teg}} \cdot u_{\text{teg}} / \text{mm}_{\text{teg}}$
- $CO_2 = \text{com}_v\cdot CO_2 \cdot \rho_{\text{teg}} \cdot u_{\text{teg}} / \text{mm}_{\text{teg}}$

Fixed concentration:
- $H_2O = 0$
- $O_2 = 0$
Boundary Conditions

Thermal analysis

- **Fixed temperature**
  \[ T = T_{\text{teg}} \]

- **Fixed temperature**
  \[ T = T_{\text{syn}} \]

- **Adiabatic wall**

- **Convective flux**

- **PRODUCT**
Computational grid

DOF \approx 500,000

Spatial discretization by no-uniform and no-structured triangular or tetrahedral elements

UMF direct method for solving linear systems
“On design” operative conditions
89 MW\textsubscript{th} (0.8 MW\textsubscript{th}/m)
Velocity field

Effectiveness of “baffles” driving TEG to the fuel injection region
“On design” operative conditions
89 MW\(_{th}\) (0.8 MW\(_{th}/m\))
Streamlines of flow

Anticlockwise vortex formation and slight pressure drop caused by the vein contraction

Recirculation chamber: fuel is used as coolant for the burner manifold
“On design” operative conditions
89 MW$_{th}$ (0.8 MW$_{th}$/m)
Concentration field of reacting species

Molar fraction of O$_2$

Molar fraction of H$_2$
“On design” operative conditions
89 MW$_{th}$ (0.8 MW$_{th}$/m)
Concentration field of product (H$_2$O)

“Anchorage” assured by the deflector wing with respect to the product formation (mixing and combustion region)
“On design” operative conditions
89 MW\text{th} (0.8 MW\text{th}/m)

Temperature is lower than the threshold (700 K) causing the Ni deposition
“On design” operative conditions
89 MW$_{th}$ (0.8 MW$_{th}$/m)
3D results – fluid dynamics

*Velocity field*
“On design” operative conditions
89 MW\textsubscript{th} (0.8 MW\textsubscript{th}/m)

3D results – thermo-chemical

- Molar fraction H\textsubscript{2} (0.8 MW\textsubscript{th})
- Molar fraction H\textsubscript{2}O (0.8 MW\textsubscript{th})
- Molar fraction O\textsubscript{2} (0.8 MW\textsubscript{th})
- Isotherms (0.8 MW\textsubscript{th})
"Turn down" operative conditions (150%)
133 MW\textsubscript{th} (1.2 MW\textsubscript{th}/m)
Streamlines of flow

Due to the higher thermal load, flow rates of incoming fluids are increased: fluid-dynamics is modified

A new little clockwise vortex is clearly observable close to the end of the deflector wing
“On design” Vs “Turn down”
Comparison of fluid dynamical fields

The highlighted new fluid structure allows TEG to come closer to the fuel injection hole improving mixing between oxidising and combustive
“Turn down” operative conditions
133 MW<sub>th</sub> (1.2 MW<sub>th</sub>/m)
Concentration field of product (H<sub>2</sub>O)

Reaction takes place close to the burner front section...
“Turn down” operative conditions
133 MW\textsubscript{th} (1.2 MW\textsubscript{th}/m)
Thermal field

... the flame get closer to the burner body determining high overheating!
“Turn down” operative conditions
133 MW\textsubscript{th} (1.2 MW\textsubscript{th}/m)

Thermal field

“On design” thermal field

Isothermal surfaces
“Turn down” operative conditions
133 MW\textsubscript{th} (1.2 MW\textsubscript{th}/m)
Temperature along symmetry axis

\begin{itemize}
\item 0.6 MW\textsubscript{th}/m
\item 1.2 MW\textsubscript{th}/m
\end{itemize}
“Turn down” operative conditions
133 MW\textsubscript{th} (1.2 MW\textsubscript{th}/m)
Temperature along the front panel

Nickel-carbonyl deposition becomes “possible” due to the high temperature of the burner manifold
Other condition potentially responsible of brisk combustion:
Slight gap between modules
Other condition potentially responsible of brisk combustion:
Slight gap between modules

Molar fraction of $O_2$ and $H_2$ in a front section of the recirculation chamber
Other condition potentially responsible of brisk combustion: Slight gap between modules

Molar fraction of $\text{H}_2\text{O}$ in longitudinal sections of the burner

$\text{H}_2\text{O}$ production
Other condition potentially responsible of brisk combustion:

Slight gap between modules

TEG leakage to the recirculation chamber lead to a brisk combustion close to the burner body

Isothermal surfaces
Conclusions

A multi-physical numerical analysis concerning fluid-dynamical, chemical and thermal behaviour of an industrial duct-burner has been performed:

- The present study underlines the needed of simulating simultaneously several interconnected aspects of physics for technological systems, in order to completely describe their operative conditions.

- Simulations well highlight as modification in fluid-dynamics, related to increasing in mass flow rate of reactants, seriously compromise flame stability. Flame triggering during “turn-down” conditions results too close to after-burners manifold, so that metal deposition and high thermal stresses could be produced.

- The onset of a dangerous brisk combustion, related to TEG leakages through out the assembled array of duct-burners, has been also detected by 3D simulations.
This research work has been developed at:

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